# Nonlinear Ultrasonic NDE

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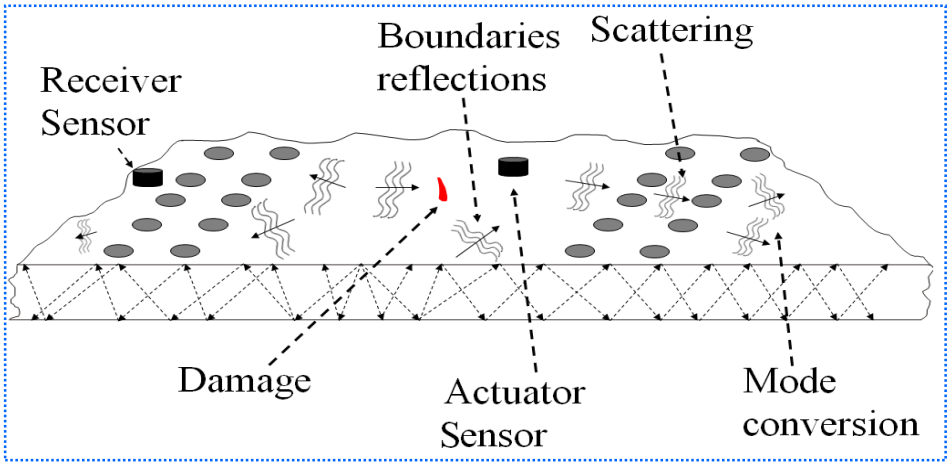
# Outline

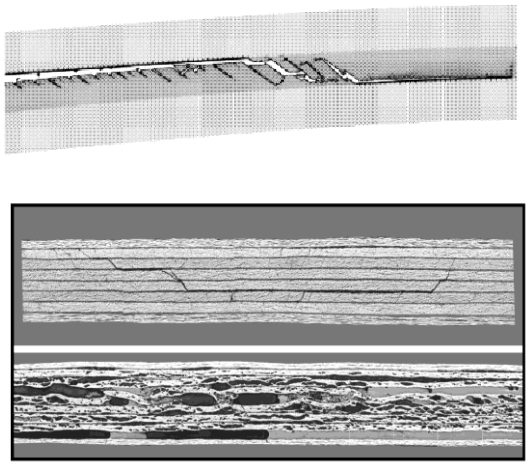
- Need for Nonlinear Ultrasonic NDE Methods
- Nonlinear Imaging Method
- 3D Multiscale Model for Nonlinear Wave Propagation
- Experimental and Numerical Results

# Need for Nonlinear Ultrasonic NDE Methods

- Reflection and scattering of primary waves at heterogeneities and discontinuities are measured
  - They work satisfactory for high acoustic impedance contrast
  - No changes of input frequency but only amplitude and phase variations

Delamination in multi-layered materials



- Micro-damages and changes in constitutive parameters (elastic moduli, sound speed) are **too sensitive** to be detected by linear ultrasonic techniques

# Need for Nonlinear Ultrasonic NDE Methods

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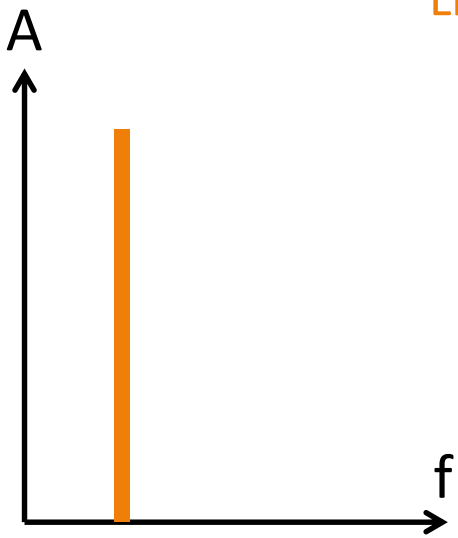
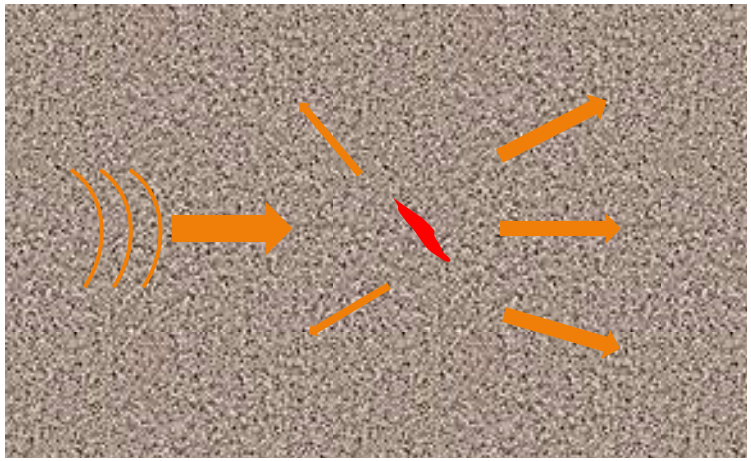
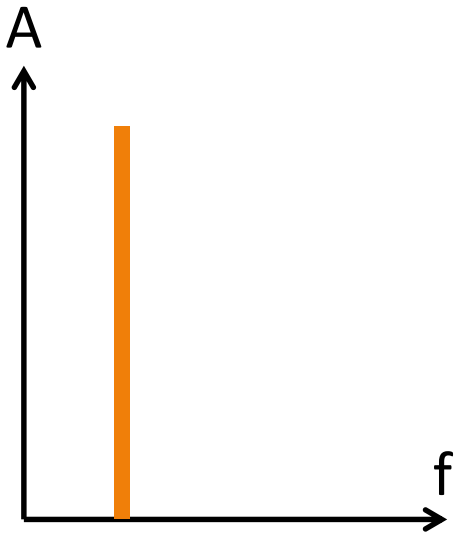
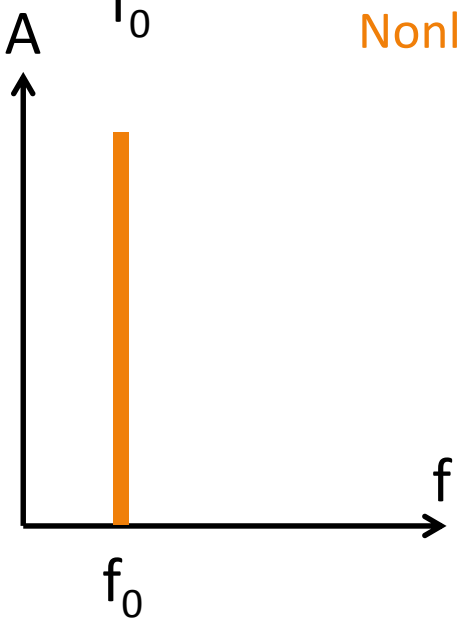
## Linear Acoustic/Ultrasonic NDE Methods

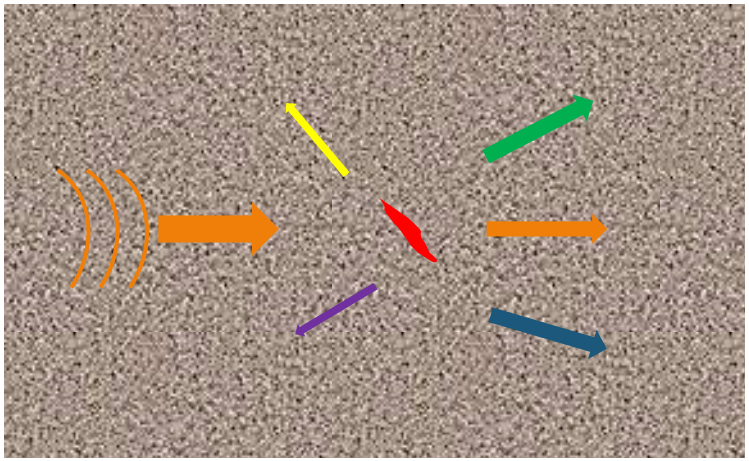


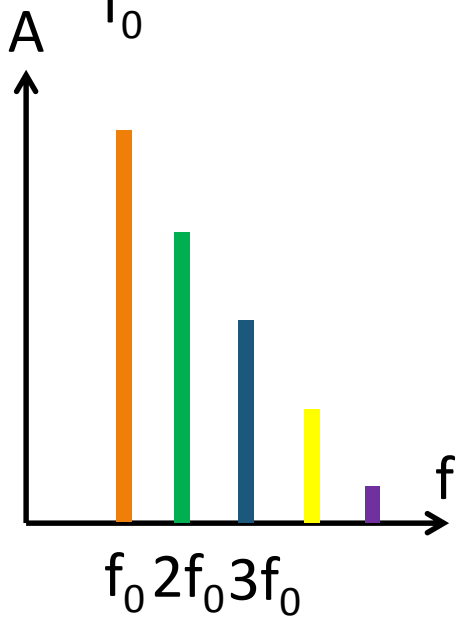






## Nonlinear Acoustic/Ultrasonic NDE Methods





# Material Anharmonic Effects

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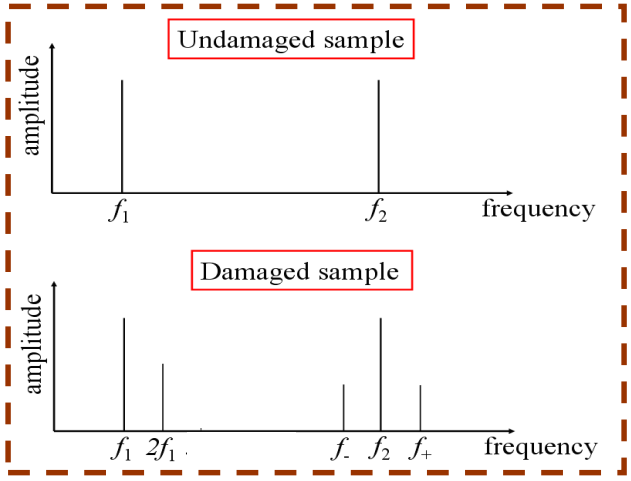
- Materials such as aluminium steel, glasses, single crystals and numerous others exhibits *anharmonic effects* when damaged (**classical nonlinear theory**, CNL )

  - They can be expressed by a nonlinear strain-stress relationship (**Landau's Theory**)
  - Using mono- or bi-harmonic excitation the interaction of the ultrasonic waves with the structural damage generates new frequency components (**Even Harmonics**)



# Material Hysteretic Effects

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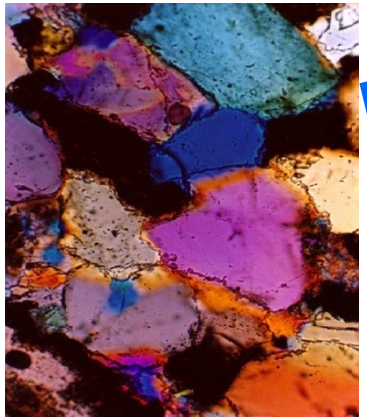
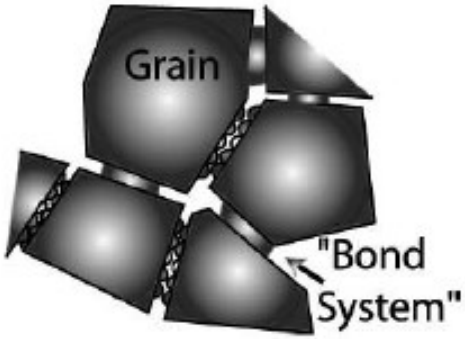
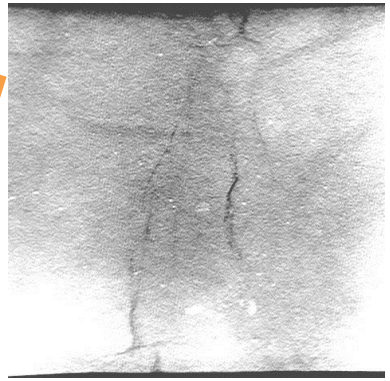
- Materials such as rock, soil, ceramics, concrete, but also damaged composite and metal structures manifest *biphasic nature* (hard grains and soft bond systems), i.e. micro-damage zones with *hysteretic nonlinearity* (**non-classical nonlinear theory**, NME)
- Physical dynamic models attribute this nonlinear behaviour to friction of crack surfaces (closure and opening of crack or a bond system)
- The nonlinear effect on the wave propagation is to create **Odd Harmonics**

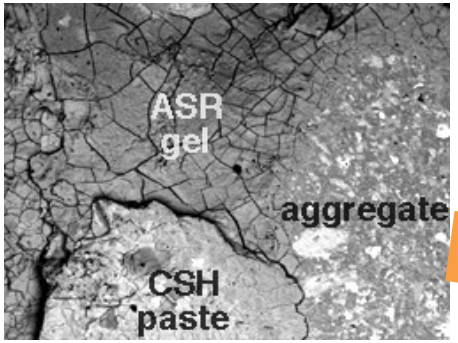


Sandstone



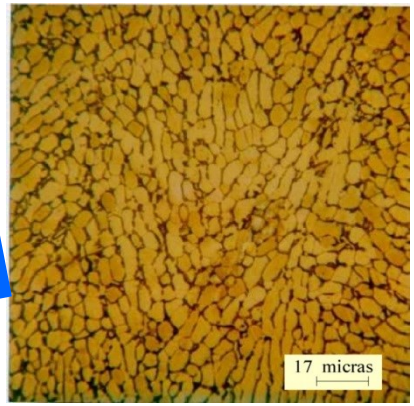

Slate



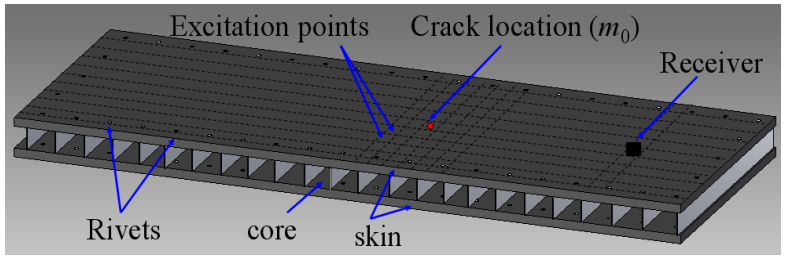


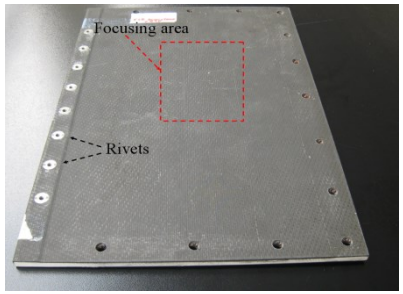

Concrete

Some Alloys



# Nonlinear NDE Ultrasonic Imaging Method



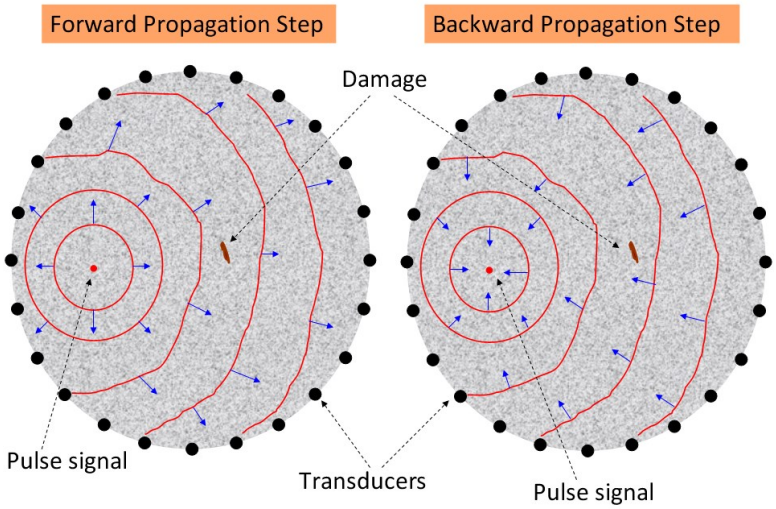

Damaged zone "focusing area" divided in a grid of *M*=7 x 6 "excitation points"

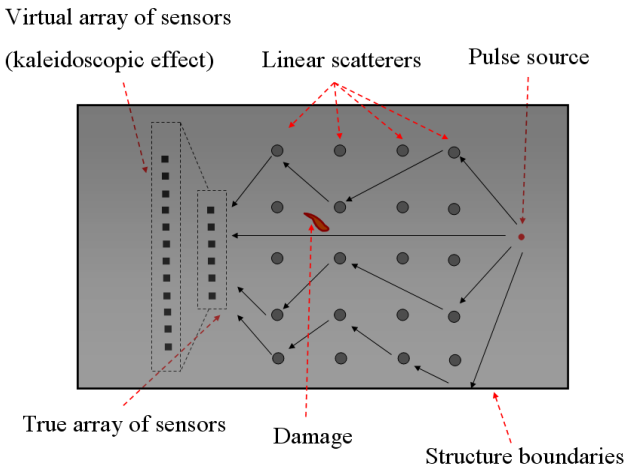
- *Third order nonlinear response* using **Phase Symmetry Analysis** (PSA) with **chirp** excitation and **Inverse Filtering** (IF)[5]


[5]**Ciampa, F.**, Meo, M. Nonlinear elastic imaging using reciprocal time reversal and phase symmetry analysis. *Journal of Acoustical Society of America*, *130* (*6*), pp. 4316-4323, 2012

# Nonlinear Inverse Filtering

- In a Inverse Filtering (IF) process an input signal is *focused back* on the nonlinear source if the output received by the transducer is *reversed* in time and emitted back to the excitation point




- The *reverberant diffuse wave field* (boundary reflections, mode conversion) in a geometrically complex medium enhances the spatial focusing of the re-emitted signals (*Kaleidoscopic effect*)
- Only **one receiver sensor** can be used for optimal refocusing

# Nonlinear Third Order Imaging Results

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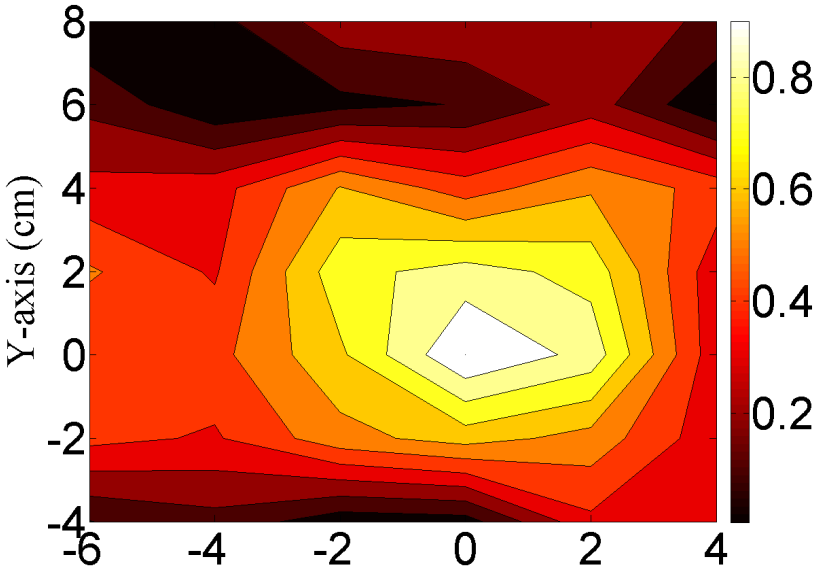
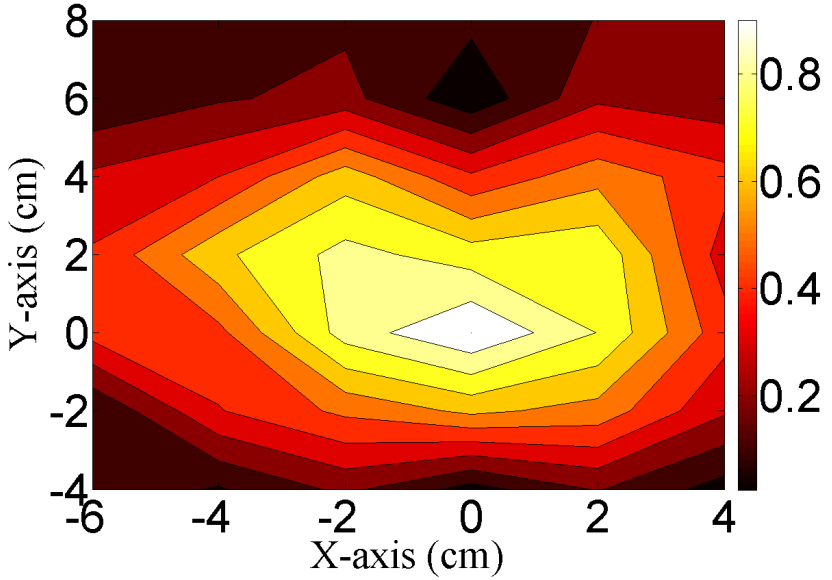
## Receiver and damage coordinates

| | X-coordinates [cm] | Y-coordinates [cm] |
|---|---|---|
| **Receiver position (case T1)** | 60 | 17 |
| **Receiver position (case T2)** | 4 | 22 |
| **Damage location** | 38 | 24 |

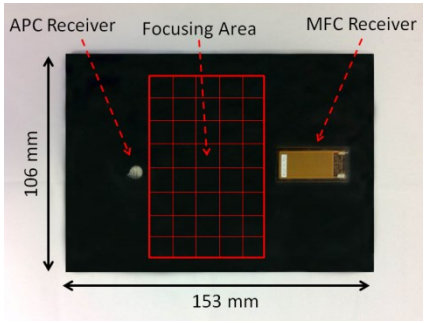



**Case T1**




**Case T2**

# Nonlinear Second Order Imaging Method

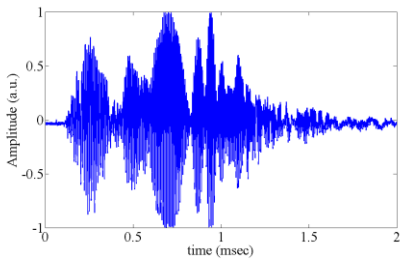



C-Scan

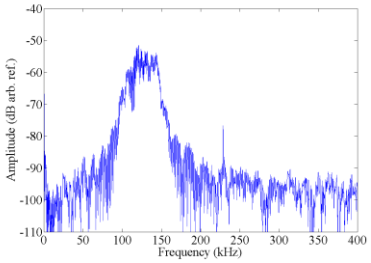
- CFRP
- 153 x 106 x 3 mm
- $[0/45/90/-45]_s$
- BVID @ *10 J*

Damaged zone “focusing area” divided in a grid of *M*=8 x 5 “excitation points”

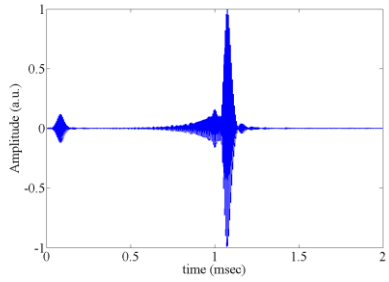
- *Second order Nonlinear Response* using Phase Symmetry Analysis




FFT




**Measured Signal**

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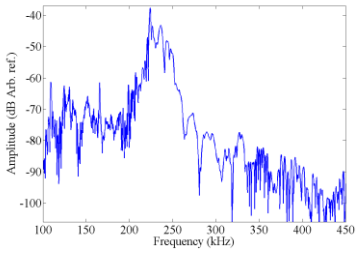


**Second Order Response with PSA**

# Nonlinear Second Order Imaging Results

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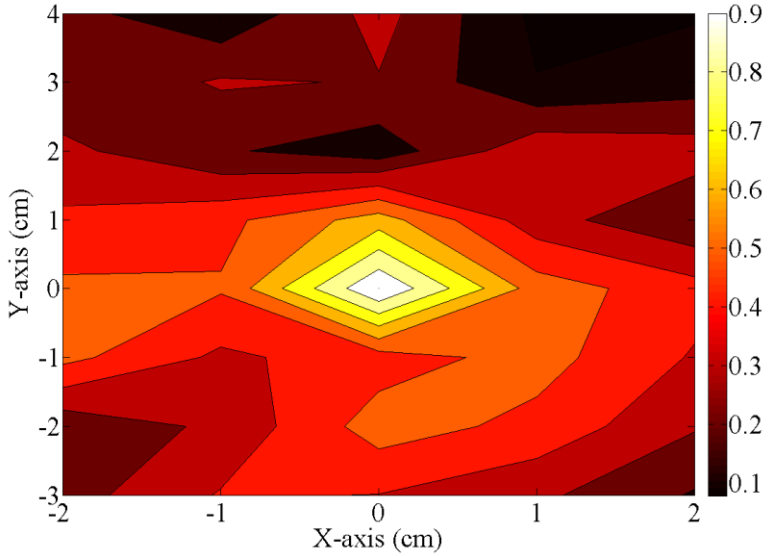
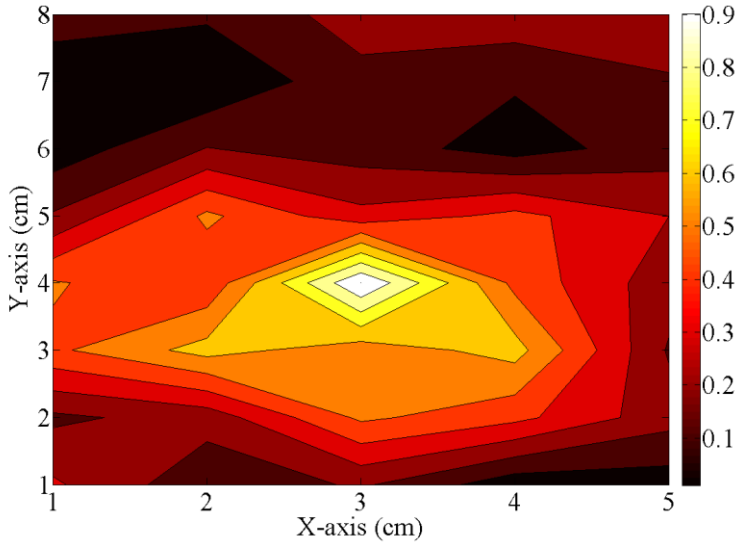
## Receiver and damage coordinates

| | X-coordinates [mm] | Y-coordinates [mm] |
|---|---|---|
| **APC sensor (case S1)** | 30 | 50 |
| **MFC sensor (case S2)** | 90 | 48 |
| **Damage location** | 59 | 53 |




**Case S1**

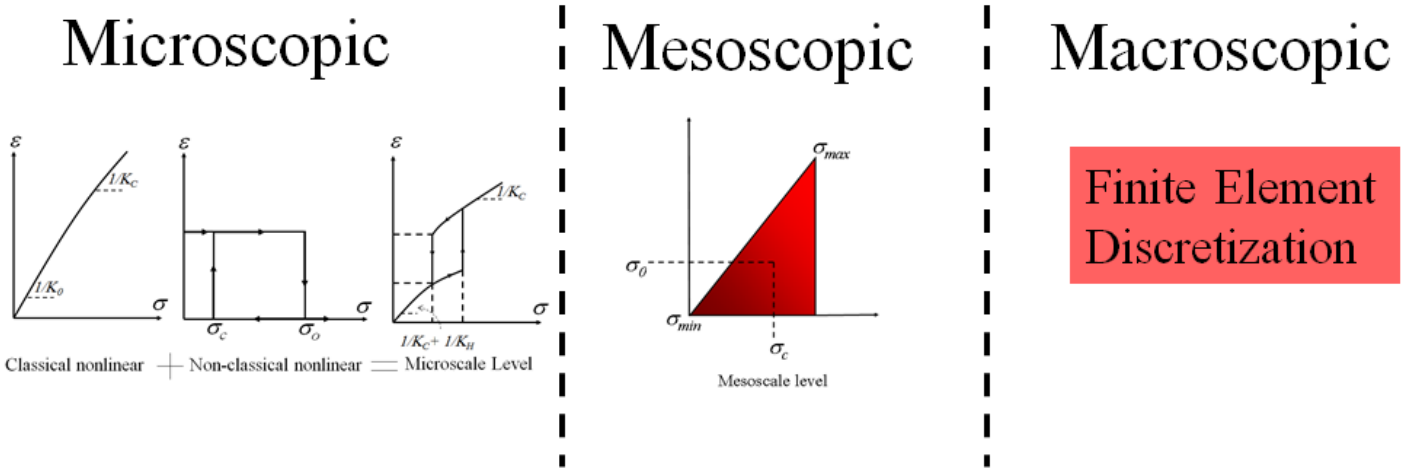



**Case S2**

# Multiscale FE Model for Nonlinear Wave Propagation

- **Multiscale material model** implemented in Finite Element (FE) able to simulate the nonlinear interaction of ultrasound waves with cracks/damage precursors

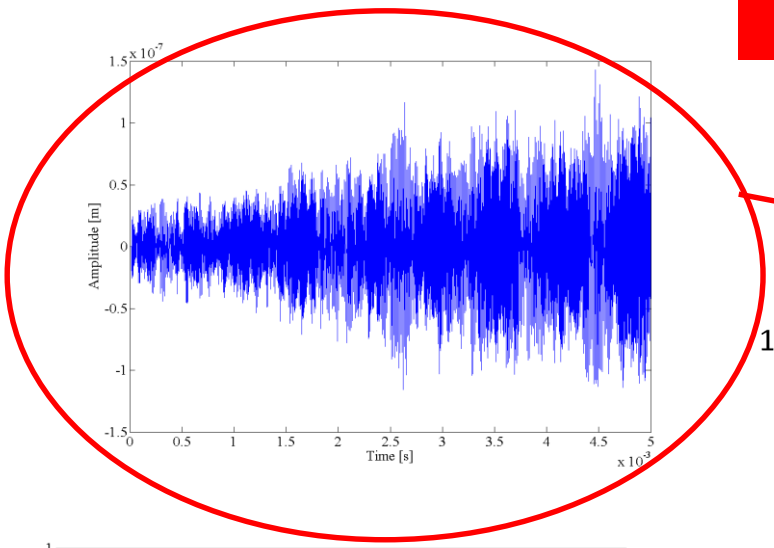
In the Multiscale model, intermediate (**mesoscopic**) material elements are introduced between the **microscopic** mechanics (micro-cracks, grain size, etc…) and the **macroscopic** structural behaviour



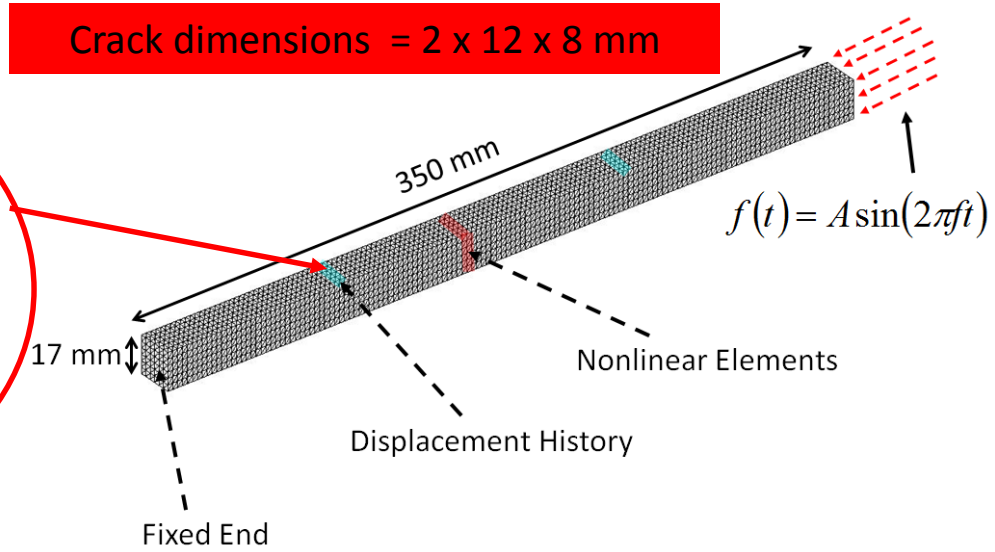

- Nonlinear effects can be simulated:
  - **Odd harmonics** – material hysteresis and discrete memory such as concrete, ceramics, sandwich structures, etc…
  - **Even Harmonics** – material anharmonic effects such as fatigue damage in metallic materials and delamination in multi-layered structures

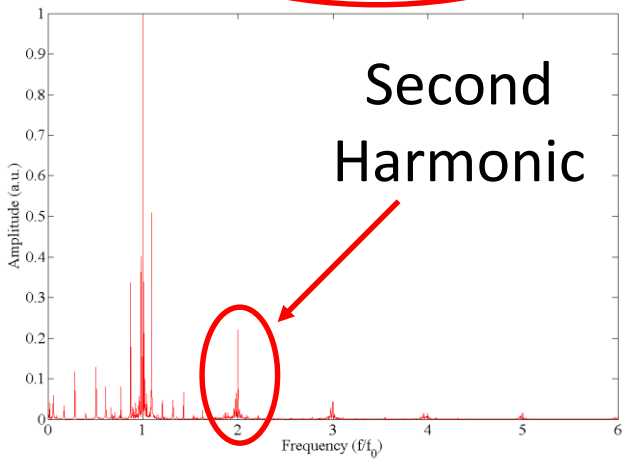
# Numerical Results – Composite Bar

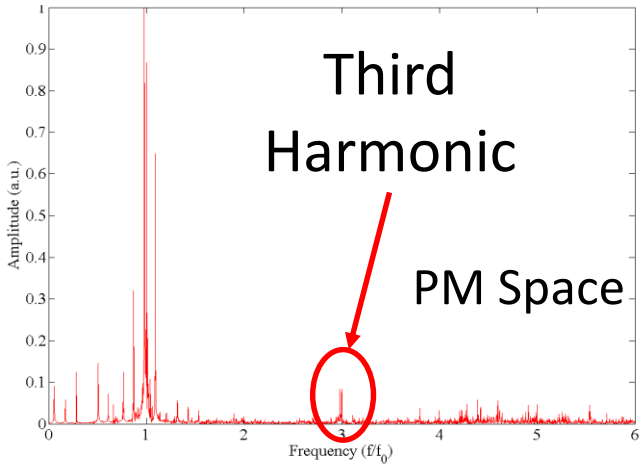
3D Numerical Results for a composite bar with in-plane harmonic wave propagation ($f_0$ = 100 kHz)




Crack dimensions = 2 x 12 x 8 mm



# Numerical Results – Isotropic and Composite Bar

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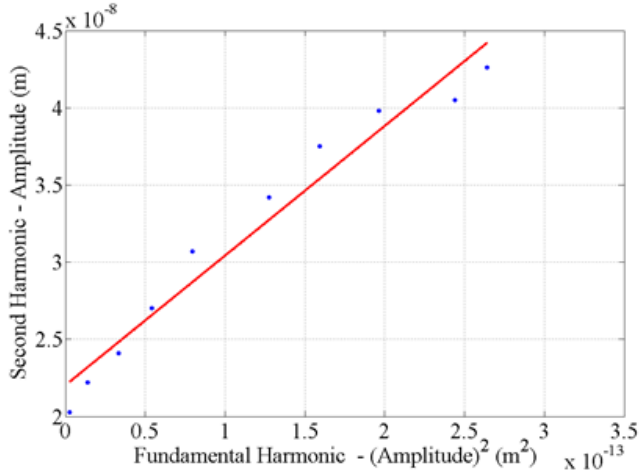
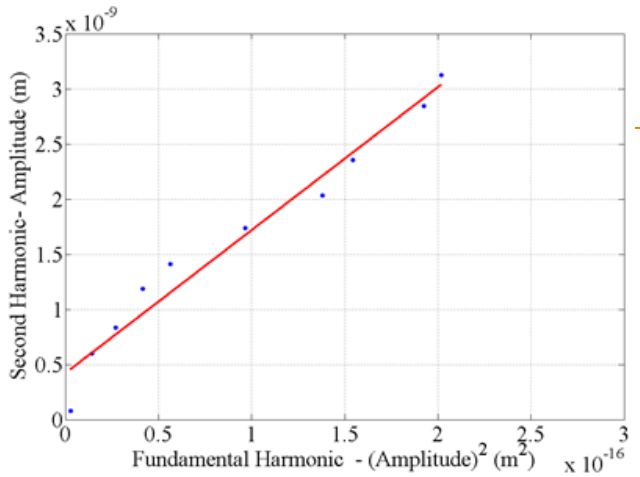
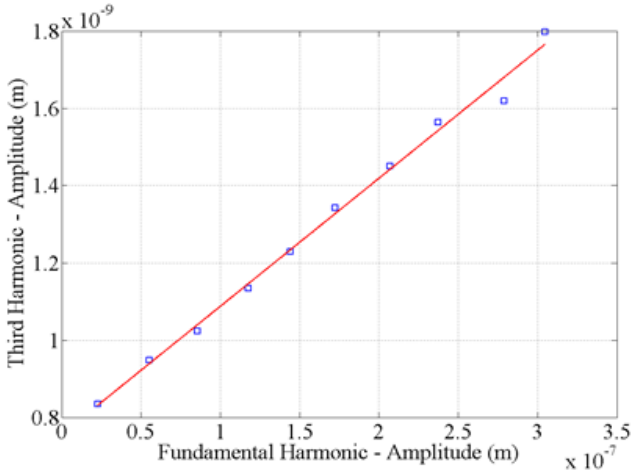
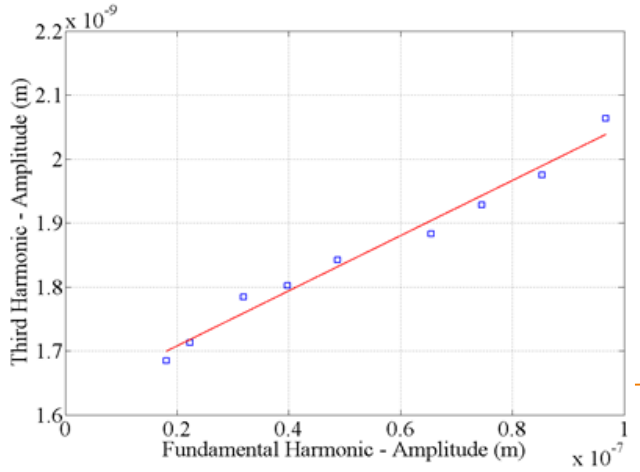
Isotropic



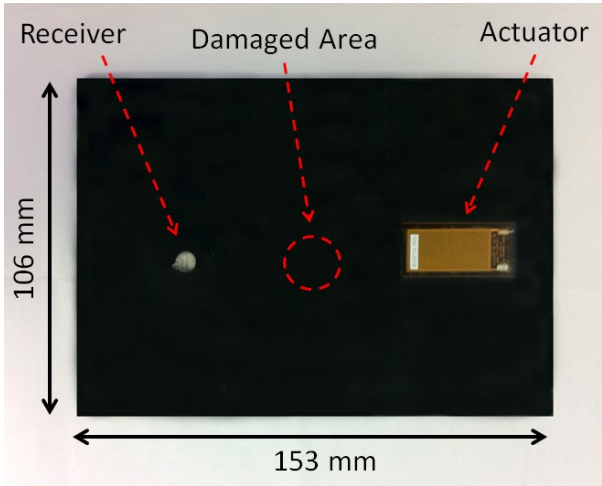



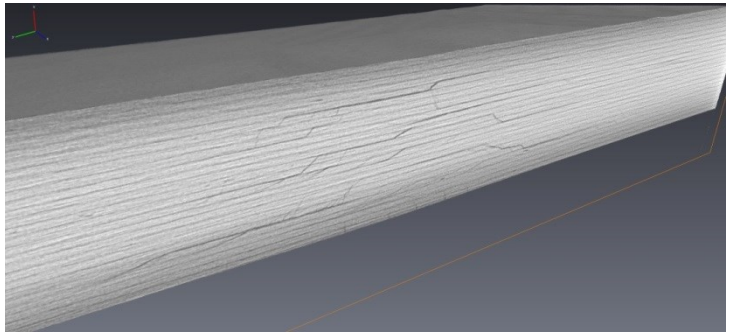



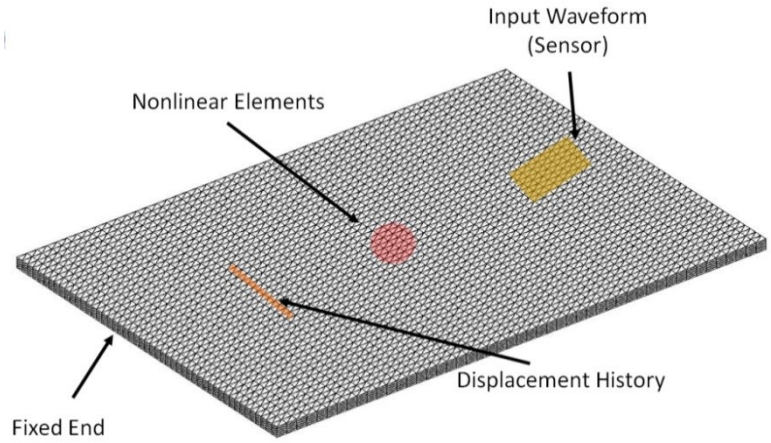

Composite

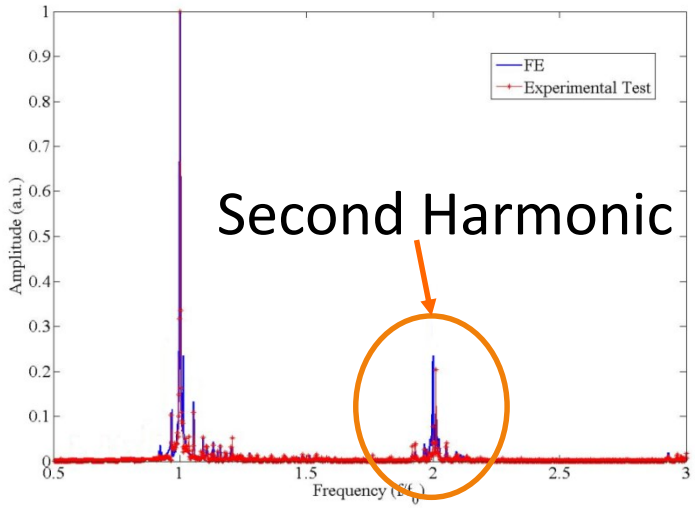
# Numerical and Experimental Results – Composite Panel




X-Ray Tomography





For Further information:

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# Thank you for your attention!!

UK Research Centre in NDE